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Insect-Plant Chemical Ecology: Detection of Plant Volatiles and Their Roles in Ecological Interactions

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Abstract

Insect-plant chemical ecology examines the dynamic interactions between insects and plants, primarily mediated by volatile organic compounds (VOCs). This article explores how insects detect plant volatiles through specialized olfactory systems, leading to behavioural responses that impact pollination, herbivory, and natural pest control. Plant volatiles serve crucial ecological roles, including deterring herbivores and attracting beneficial insects, and their application in sustainable agriculture is promising, particularly through methods like push-pull systems and genetically modified crops. Future research should focus on the molecular mechanisms of volatile perception, field-based studies, and innovative agricultural strategies leveraging plant volatiles for effective pest management, which can ultimately enhance agricultural sustainability and ecosystem resilience.

Introduction

Insect-plant chemical ecology is a fascinating field that explores the intricate interactions between insects and plants, primarily mediated by volatile organic compounds (VOCs). These interactions are crucial for processes such as pollination, herbivory and pest control and have significant implications for agricultural practices. VOCs are emitted by plants in response to external stimuli, such as herbivore attacks or pathogen infections, acting as signals that can modulate insect behaviour and interactions among multiple trophic levels. This review delves into how insects detect plant volatiles, the ecological roles of these interactions and their practical applications in agriculture, with a focus on indigenous aromatic crops like spices and medicinal plants. Insects possess highly specialized olfactory systems that enable them to detect and respond to plant volatiles. These volatiles, which include terpenoids, phenylpropanoids and green-leaf volatiles, are emitted by plants in response to environmental cues, such as herbivore attacks or pathogen infections (Das *et al*., 2013) (Serdo, 2024).

Detection of Plant Volatiles by Insects

1. **Perception Mechanisms**: Insects use chemosensory proteins (CSPs) and odorant-binding proteins (OBPs) to perceive plant volatiles. These proteins bind to odorant molecules and facilitate their transport to odorant receptors in the antennae (Lei *et al*., 2024; Qian *et al*., 2024). For example,

in *Bactrocera dorsalis*, a highly invasive fruit fly, the antennae-enriched CSP, BdorCSP3 plays a critical role in detecting host plant volatiles like methyl eugenol and β-caryophyllene (Lei *et al*., 2024).

2. **Behavioural Responses**: Once detected, these volatiles elicit specific behavioral responses in insects, such as attraction to food sources, mates or oviposition sites. For instance, the fall armyworm (*Spodoptera frugiperda*) is repelled by certain volatiles emitted by *Desmodium* species, which are used in push-pull strategy in agriculture to manage pest populations (Odermatt *et al*., 2024).
3. **Environmental Influences**: Environmental factors, such as temperature, humidity and wind, can influence the emission and perception of plant volatiles. These factors often determine the effectiveness of volatile-mediated interactions in natural settings (Serdo, 2024; Qian *et al*., 2024).

Ecological Roles of Plant Volatiles

Plant volatiles play a pivotal role in mediating interactions between plants, insects and other organisms, thereby contributing significantly to ecological balance and agricultural productivity. Floral volatiles, particularly terpenoids and benzenoids serve as key attractants for pollinators such as bees, butterflies and moths, often functioning synergistically with visual cues like flower color and morphology to guide pollinators to nectar sources (Das *et al*., 2013; Faheem *et al*., 2004). In addition to facilitating pollination, plants emit herbivore-induced plant volatiles (HIPVs) upon herbivore attack, which can directly deter herbivores or indirectly attract their natural enemies, including parasitoids and predators (Zhou and Jander, 2021). For instance, maize plants damaged by fall armyworm infestation release HIPVs that attract parasitoid wasps, enhancing biological control.

Beyond these direct and indirect defences, plant volatiles also mediate complex tri-trophic interactions, recruiting beneficial insects that help suppress herbivore populations through the release of compounds such as β-ocimene and β-caryophyllene (Niu *et al*., 2024). Furthermore, volatiles facilitate plant-to-plant communication; undamaged plants can perceive airborne signals from neighboring damaged plants and pre-emptively activate their own defense responses, a phenomenon known as “priming” (Das *et al*., 2013; Arimura and Uemura, 2024). Collectively, this sophisticated chemical signalling mechanisms not only bolster individual plant defense but also strengthen the resilience of entire ecosystems.

Practical Applications in Agriculture

The understanding of plant volatile-mediated interactions has led to the development of innovative strategies for sustainable agriculture. These strategies aim to reduce reliance on chemical pesticides and promote eco-friendly pest management practices.

1. Push-Pull Agriculture

Push-pull systems utilize plant volatiles to repel pests and attract their natural enemies. For example, intercropping with *Desmodium* species repels the fall armyworm (*Spodoptera frugiperda*) and attracts parasitoids that prey on the pest (Odermatt *et al*., 2024) (Figure 1). This approach has been successfully implemented in maize cultivation to reduce herbivory damage.

2. Genetically Modified Crops

Genetic modification of crops to alter their VOC emission profiles is another promising strategy. Crops with enhanced VOC emissions can attract beneficial insects or repel pests, providing a

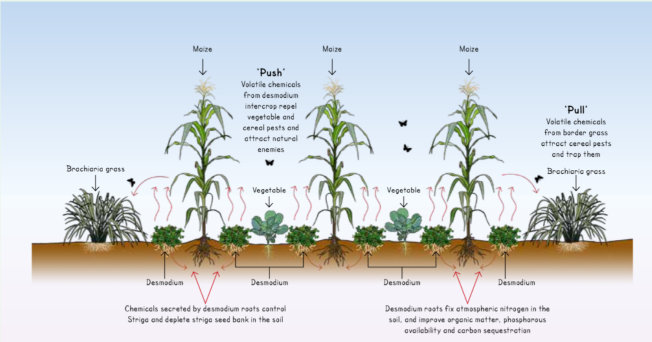

Figure 1. Push-Pull strategy against fall armyworm (*Spodoptera frugiperda*) (Sobhy *et al.,* 2022)

sustainable alternative to conventional pest control methods (Maurya, 2020; Arimura and Uemura, 2024).

3. Volatile-Based Pest Control

Plant volatiles can be used as attractants or repellents in pest control. For instance, synthetic formulations of plant volatiles can be used in traps to capture pest insects or disrupt their mating behaviours (Maurya, 2020; Qian *et al*., 2024). This approach is particularly effective for managing invasive pests like *Bactrocera dorsalis* (Lei *et al*., 2024). Several examples of plant volatiles and their associated herbivores are listed in Table 1.

4. Indigenous Aromatic Crops

Indigenous aromatic crops, such as spices and medicinal plants are rich sources of bioactive volatiles. These compounds have been used for centuries in traditional agriculture to repel pests and attract pollinators. Modern research has validated the efficacy of these traditional practices, providing a scientific basis for their integration into contemporary agricultural systems (Teranishi *et al*., 1993; Makhlouf *et al*., 2024).

Insights into Ecological Relationships

The study of plant volatile-mediated interactions has provided valuable insights into the ecological relationships between plants and insects, which are critical for understanding the complex dynamics of agricultural ecosystems and developing sustainable management strategies. The chemo diversity of plant volatiles is shaped by evolutionary pressures, including herbivore pressure and environmental conditions, with domestication and coexistence with herbivores significantly influencing the volatile profiles emitted by plants (Thompson *et al*., 2024). Understanding these evolutionary forces is crucial for breeding crops with enhanced resistance to pests.

Plant volatiles also mediate multitrophic

Table 1. Plant volatiles and their associated herbivores

Plant Volatile	**Associated Herbivore**	**Notes**
β-Caryophyllene	*Agrotis segetum*	Attracts the parasitoid *Microplitis mediator*, enhancing pest control (Li *et al.,* 2022).
Linalool	Various herbivores	Emitted in response to herbivore attack, serving as a deterrent (War *et al.,* 2011).
Green Leaf Volatiles	*Manduca sexta, Tupiocoris notatus*	Elicit predator responses, varying with time of day (Joo *et al.,* 2018).
Nonanal	*Agrotis segetum*	Part of the volatile blend that attracts natural enemies (Li *et al.,* 2022).
Terpenoids	Various herbivores	Serve as chemical defenses and attract parasitoids (Rani and Sulakshana, 2017).

interactions across different trophic levels, influencing the behaviour of herbivores as well as their natural enemies. For instance, terpenoids such as α-pinene and β-myrcene have been shown to attract predators and parasitoids that help regulate pest populations (Niu *et al*., 2024). Additionally, eco-evolutionary factors like plant domestication and long-term herbivore coexistence can either enhance or diminish volatile diversity, thereby affecting the ecological effectiveness of plant defences (Thompson *et al*., 2024; Makhlouf *et al*., 2024).

Multitrophic semiochemical interactions

Multitrophic semiochemical interactions among plants, insects, and associated microorganisms are complex and pivotal in shaping ecological dynamics. These interactions involve chemical signals that influence herbivore behaviour, plant defence mechanisms, and the roles of microbial communities. Plants emit volatile organic compounds (VOCs) that attract or repel herbivores and their natural enemies, influencing foraging and oviposition behaviours. Microbial associations can modify these chemical cues, enhancing or diminishing plant attractiveness to herbivores. Plant-associated microorganisms can induce significant phenotypic changes in plants, affecting their quality as hosts for herbivores. Some insects utilize plant secondary metabolites for prophylactic and therapeutic purposes, enhancing their resistance to pathogens (Shikano, 2017). Understanding these multitrophic interactions can inform the development of biotechnical control methods, such as using semiochemicals to manage pest populations effectively (Gross *et al.,* 2019). The integration of microbial and entomopathogenic interactions into pest management strategies can enhance plant fitness and agricultural sustainability (Shikano, 2017).

Future Directions and Research Gaps

While significant progress has been made in understanding plant volatile-mediated interactions, several research gaps remain that must be addressed to advance the field and foster innovative agricultural practices. Further investigation is needed into the molecular mechanisms underlying volatile perception and signalling, particularly concerning the role of chemosensory proteins in insect olfaction and the molecular pathways involved in volatile biosynthesis (Lei *et al*., 2024; Qian *et al*., 2024). Moreover, most current knowledge is derived from controlled laboratory studies, highlighting the urgent need for more field-based research to capture the complexities and variability of volatile-mediated interactions in natural ecosystems (Makhlouf *et al*., 2024). Additionally, the development of sustainable agricultural practices leveraging plant volatiles remains an underexplored area; promising strategies include the application of microbial volatiles and the use of genetically modified crops engineered to enhance volatile organic compound (VOC) emissions for improved pest management (Maurya, 2020; Makhlouf *et al*., 2024).

Conclusion

Insect-plant chemical ecology is a vital area of research with significant implications for agriculture and ecosystem management. Plant volatiles play a central role in mediating interactions between plants and insects, influencing processes such as pollination, herbivory, and pest control. By understanding these interactions, researchers can develop innovative strategies for sustainable agriculture, such as push-pull systems and volatile-based pest control. However, further research is needed to address existing gaps and unlock the full potential of plant volatiles in agricultural applications.

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